

# Energy Losses Associated With Abrupt Enlargements in Pipes

With special reference to the influence of boundary roughness

By CARL E. KINDSVATER

RIVER HYDRAULICS

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GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1369-B



**UNITED STATES DEPARTMENT OF THE INTERIOR**

**STEWART L. UDALL** *Secretary*

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## RIVER HYDRAULICS

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# ENERGY LOSSES ASSOCIATED WITH ABRUPT ENLARGEMENTS IN PIPES

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By CARL E. KINDSVATER <sup>1</sup>

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### ABSTRACT

This report describes the results of a simple experimental investigation of the flow of water through abrupt, concentric enlargements in circular pipes. Particular attention is paid to the influence of pipe-wall roughness and to methods of computing the energy loss resulting from enlargements. The investigation grew out of a laboratory study of the hydraulics of bridge waterways, which resulted in conjecture regarding the influence of boundary roughness on the expanding flow downstream from open-channel constrictions. To avoid experimental complications caused by free-surface characteristics of open-channel flow, this phase of the study was converted to an investigation of enlargements in pipes.

In the conventional procedure for computing the total loss of energy in a pipe system containing an enlargement, a special enlargement loss is added to the normal resistance loss in the adjoining pipes. The enlargement loss is computed from the well-known Borda-Carnot equation, and the resistance loss is computed from a formula such as the Darcy-Weisbach formula. The procedure is based on several questionable assumptions.

A total of 115 tests was made with 6 different enlargement ratios and 3 degrees of pipe-wall roughness. A special series of tests was made with a rough sleeve in the separation zone at the beginning of the enlargement.

Nondimensional total-loss coefficients derived from the tests are compared with coefficients obtained by the conventional computation procedure. From this comparison, it is concluded that the conventional method of computing the energy loss in pipes is adequate for practical use. It is apparent that pipe-wall roughness does not have an independent influence on the diffusion process.

### INTRODUCTION

Since 1951 the U.S. Geological Survey has been engaged in an intensive study of the hydraulics of bridge waterways. Of primary importance to the study was a laboratory investigation of elementary width constrictions in simple channels (Kindsvater and Carter, 1955; Kindsvater, Carter, and Tracy, 1953; Tracy and Carter, 1955). Although the bridge waterway was used to define the scope of the

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laboratory research, an exhaustive study of the almost unlimited number of natural boundary conditions was obviously impractical. Consequently, many secondary or unusual variables were excluded from the scope of the investigation.

One phase of the bridge-waterway investigation included a detailed consideration of the abruptly enlarged stream downstream from the constriction. Related to this was considerable conjecture regarding the influence of channel roughness on the diffusion process. Because it was believed to be of secondary importance, and because a laboratory investigation of this question would involve special equipment and instrumentation, it was excluded from the scope of the principal investigation. Subsequently, however, it was selected by graduate students as a suitable topic for research.

In its simplest form, the problem which had been extracted from the bridge-waterway investigation was the question of the effect of boundary roughness on the flow downstream from abrupt enlargements in open channels. Of particular practical interest was the influence of boundary roughness on the total energy loss resulting from the enlargement. Preliminary analysis revealed that a laboratory investigation of the problem would be unnecessarily complicated by certain free-surface characteristics of open-channel enlargements. Thus, the research which is the basis for this report was concerned exclusively with abrupt enlargements in circular pipes.

Because of the dominant interest in the energy-loss characteristics of enlargements, the method of investigation selected for the laboratory studies involved simply the measurement of total head loss for a variety of enlargement ratios, Reynolds numbers, and pipe-wall roughnesses. However, it was hoped that variations in energy loss could be correlated with the experimental variables to give information regarding the flow mechanism.

#### ACKNOWLEDGMENTS

All of the experimental work was done in the Hydraulics Laboratory, School of Civil Engineering, Georgia Institute of Technology, Atlanta, Ga. The principal investigators were graduate students in the School of Civil Engineering. The first investigator was Trafton W. Fleetwood, Jr.,<sup>2</sup> whose work revealed inadequacies in equipment and instrumentation. The second investigation, with improved equipment, was performed by Benjamin L. Kittle.<sup>3</sup> Kittle's laboratory tests were limited to enlargements in a smooth pipe. His apparatus was subsequently used by Fred H. Ruggles on a special

<sup>2</sup> Fleetwood, T. W., 1955, Abrupt enlargements in smooth and rough pipes: Georgia Inst. Technology Master's degree thesis, 62 p., 28 figs.

<sup>3</sup> Kittle, B. L., 1956, Abrupt enlargements in circular pipes: Georgia Inst. Technology Master's degree thesis, 59 p., 22 figs.

problem which included tests on pipes with two degrees of sand roughness. The experimental data used for this report are the data obtained by Kittle and Ruggles. Fleetwood's work was partly supported by the U.S. Geological Survey. Others who assisted in the acquisition of miscellaneous data and in the preparation of the report include Geological Survey engineers Jacob Davidian, Frederick Kilpatrick, and William Emmett. Homer Bates, laboratory technician, constructed the nozzles and special instruments used in the investigation. All work was carried out under the direction of the writer.

### PRELIMINARY CONSIDERATIONS

The purpose of this investigation was to study the flow of water through abrupt concentric enlargements in smooth and rough circular pipes, with particular attention to the total energy loss which results. In the conventional procedure for computing the total energy loss in a pipe containing an enlargement, a special enlargement loss is added to the normal resistance loss in the adjoining pipes. The resistance loss is computed from one of several formulas which involve coefficients derived from laboratory studies of uniform flow. One of the most common is the Darcy-Weisbach formula,

$$H_f = f \frac{L V^2}{D 2g}, \quad (1)$$

in which  $H_f$  is the head loss (loss of energy in ft-lbs per lb),  $f$  is a resistance coefficient which depends generally on wall roughness and the pipe Reynolds number,  $L$  is the length of the pipe,  $D$  is the diameter of the pipe, and  $V$  is the average velocity in the pipe cross section.

The enlargement loss is computed from the Borda-Carnot equation,

$$H_B = K_B \frac{(V_1 - V_2)^2}{2g} = K_B \left( \frac{A_2}{A_1} - 1 \right)^2 \frac{V_2^2}{2g}, \quad (2)$$

in which  $H_B$  is the head loss attributed to the enlargement,  $K_B$  is a coefficient usually taken to be unity if the enlargement is abrupt,  $V_1$  and  $A_1$  are the average velocity and area, respectively, at a cross section upstream from the enlargement, and  $V_2$  and  $A_2$  are corresponding quantities at a section downstream from the enlargement. The classic derivation of the Borda-Carnot equation, which is based on the one-dimensional energy and momentum equations, is shown in nearly every textbook on elementary fluid mechanics.

A critical review of the conventional computation procedure results in the following observations:

1. The use of a uniform-flow equation to evaluate the resistance loss on both sides of the enlargement is in contradiction with the fact

that the flow is nonuniform for a considerable distance downstream from the enlargement.

2. The tangential force due to boundary shear is neglected in the derivation of the Borda-Carnot equation. Thus, variations in wall roughness are meaningless in terms of that equation.
3. The Borda-Carnot equation does not take into consideration the effect of nonuniform velocity distribution on the energy and momentum flux at the terminal cross sections.
4. Actually, there is no physical basis for the assumption that the total energy loss can be separated into independent components.

It is apparent that any errors related to these observations must be either negligible or compensating if the conventional computation procedure is to be applied successfully to a full range of practical conditions.

### REVIEW OF PREVIOUS RESEARCH

The technical literature of hydraulics contains the results of several investigations of abrupt enlargements in pipes. A brief review of selected references is pertinent as background for this investigation.

Notable among those who attempted to test the accuracy of the Borda-Carnot equation are Gibson (1910, 1912) and Archer (1913). Both of these investigators used the customary procedure for separating the enlargement loss from the total loss in the test pipe. Neither took into account the influence of upstream flow conditions, the Reynolds number of the flow, or the relative roughness of the boundaries.

Gibson's tests were made with small, smooth pipes covering a range of area ratios,  $A_2/A_1$ , from 2.25 to 10.96. He concluded that the coefficient  $K_B$  (eq 2) "increases slightly with the ratio of enlargement and, in pipes with the same ratio of enlargement, is greater the smaller the pipe" (Gibson, 1952, p. 91). Values of  $K_B$  recommended by Gibson varied from 0.95 ( $A_2/A_1=2.25$ ) to 1.04 ( $A_2/A_1=10.96$ ).

Archer's tests with small brass pipes covered a range of values of  $A_2/A_1$  from 1.45 to 9.32. He concluded that the Borda-Carnot equation gave results which were too small for low velocities and small values of  $A_2/A_1$  and too large for high velocities and large values of  $A_2/A_1$ . From a questionable extrapolation of his test results, he presented a table of recommended values of  $K_B$  which varied from 1.22 ( $A_2/A_1=1.25$ ,  $V_1=2$  ft per sec) to 0.75 ( $A_2/A_1=\infty$ ,  $V_1=80$  ft per sec). Thus, Archer contradicts Gibson's conclusions. According to King (1954, chap. 6, p. 17), Archer's results were substantiated by tests made at the University of Michigan.

Schütt (1926) concluded that the conventional procedure (with  $K_B=1.0$  in the Borda-Carnot equation) would yield results accurate

to within 1 percent. Schütt's tests covered a comparatively small range of discharges and four enlargement ratios varying from 2.8 to 8.8. His equipment was generally superior. It is noted, for example, that he used short machined nozzles at the entrance to the enlargement, and the size of his pipe (about 6-inch diameter) was larger than that used by most other investigators. However, the significance of his conclusions is doubtful in view of a questionable method used to adjust values of  $A_1$  for contraction beyond the end of the nozzles.

A more recent study by Kalinske (1947) was concerned primarily with the mechanism of energy transformation in enlargements. The results of three tests on a single abrupt enlargement ( $A_2/A_1=3$ ) included information on the distribution of velocity and pressure and the rate of energy dissipation in the turbulent wake downstream from the enlargement. From his tests Kalinske concluded that the principal energy loss occurs at the interface between the entering jet and the eddying fluid in the separation zone. He also demonstrated that the velocity distribution upstream from the enlargement has considerable influence on the energy loss in the enlargement. A valuable adjunct to his report are the comments and references contained in the published discussions.

## LABORATORY INVESTIGATION

### EXPERIMENTAL EQUIPMENT

#### GENERAL

Experiments made as a part of this investigation were performed in the hydraulics laboratory of the Georgia Institute of Technology. The arrangement of laboratory equipment used for the tests is shown in figure 1 and plate 3.

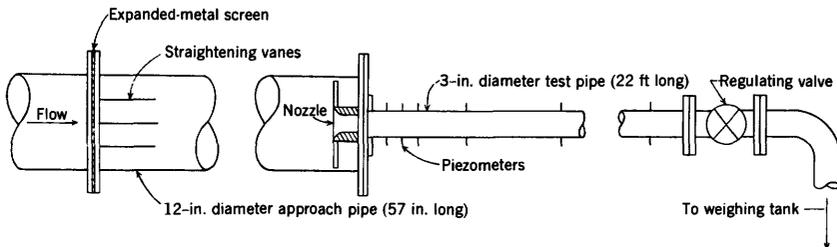


FIGURE 1.—Arrangement of laboratory equipment.

The test reach consisted of a short nozzle at the entrance to the enlargement and a 22-ft length of 3-inch pipe downstream from the enlargement. The approach to the test section consisted of a 57-inch length of 12-inch pipe equipped with straightening vanes and baffles

at the upstream end to reduce velocity nonuniformities at the entrance to the enlargement. The rate of flow was controlled with a gate valve located in the 3-inch pipe downstream from the test section.

The connecting pipe was arranged so that the laboratory's constant-head recirculating system could be used for most discharges. For the larger rates of flow the constant-head tank was bypassed with a pipeline connected directly to the pumps. The maximum discharge used in the tests was 1.33 cfs.

Electrically operated weighing-tank equipment was used for the measurement of discharges. Piezometric-head differences were measured with precision manometers.

#### NOZZLES

Nonuniformities in the entering stream were reduced by the use of short, smooth, machined aluminum nozzles instead of pipes upstream from the enlargement. Six nozzles were used to obtain a representative coverage of a reasonable range of enlargement ratios.

Plate 3*B,C* shows photographs of the nozzle and a typical entrance assembly. Figure 2 shows details of nozzle construction and installation.

Installed in the test section, a nozzle was mounted on a flange plate which was drilled to match the adjoining flanges on the approach pipe and the test pipe. A collar was affixed to the upstream end of the nozzle to provide a plane surface tangent to the elliptical curve of the nozzle entrance. Each nozzle was equipped with four piezometers. The piezometers were equally spaced on the circumference of the cylindrical throat of the nozzle, in a plane which bisected the length of the cylindrical surface.

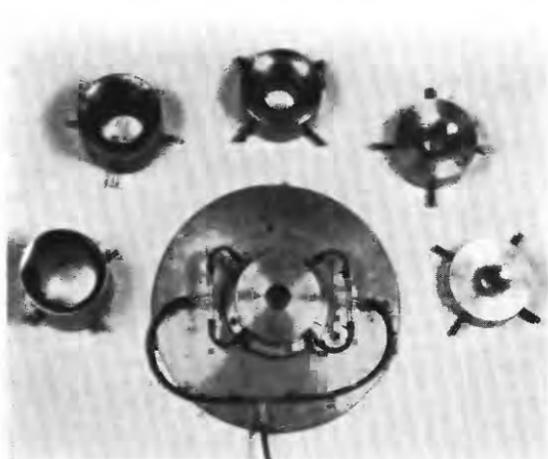
Great care was taken in the construction of the nozzles, particularly to ensure that the throats were perfect cylinders. The nozzles were made from solid aluminum stock. They were highly polished after machining. The largest nozzle was 4 inches long. Smaller nozzles were shorter, but the cylindrical part was at least 1 inch long. The finished diameter of the throat was determined as the average of several measurements with an inside micrometer.

#### TEST PIPES

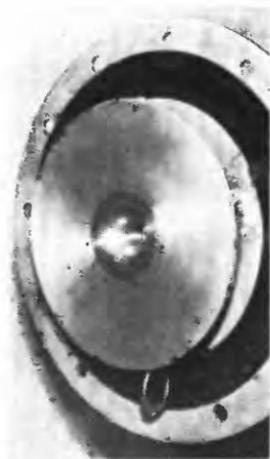
The pipe used as the downstream part of the test section for all the experiments was a 22-ft length of 3-inch-diameter extruded-aluminum pipe. It is shown in plate 3*A*. For an earlier investigation the pipe had been ground with a cylinder hone to ensure smoothness and to make it as nearly circular in cross section as possible. Four piezometers were located at each of 14 sections along the length of the pipe. Sections near the enlargement were more closely spaced than the



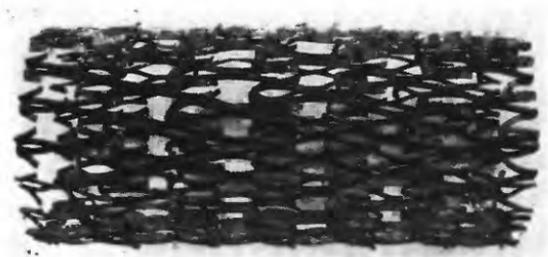
A. Laboratory arrangement.



B. Nozzles, with downstream view of typical assembly.



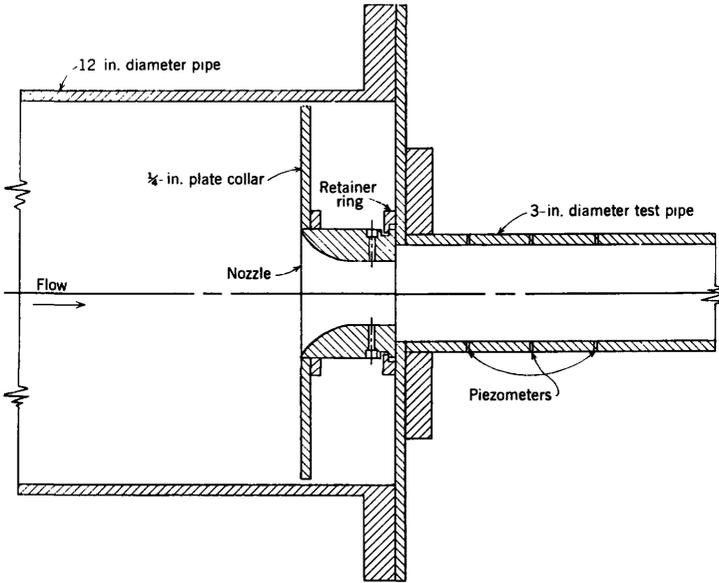
C. Upstream view of typical nozzle assembly.



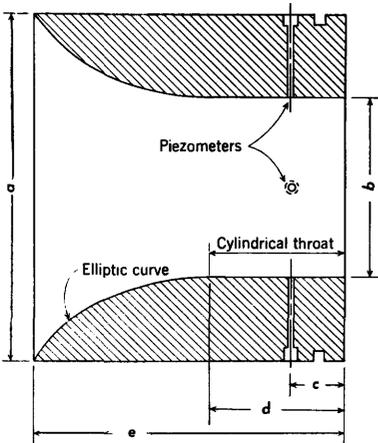
D. Expanded-metal sleeve, side view.



E. Expanded-metal sleeve, end view.



A



B

Nozzle no.	Nozzle dimensions (inches)				
	a	b	c	d	e
1	4	2.508	0.84	1.67	4.17
2	4	2.009	.67	1.33	3.33
3	4	1.499	.50	1.00	2.50
4	4	1.201	.50	1.00	2.20
5	4	1.004	.50	1.00	2.00
6	4	.752	.50	1.00	1.75

FIGURE 2.—Details of nozzle construction and installation. A, entrance assembly; B, nozzle.

others. The piezometers were one-sixteenth of an inch in diameter, drilled perpendicular to the pipe wall, and honed to prevent burrs at the inner pipe-wall orifice. The four piezometers at each section were connected through a manifold to the manometer.

For the smooth-wall tests the test-pipe diameter was measured with a cylinder gage calibrated to read thousandths of an inch. Diameter measurements were made on 2 perpendicular axes at 60 different sections over the length of the pipe. The average diameter determined in this manner was 3.057 inches.

For the rough-wall tests, screened crushed-granite sand was glued with varnish to the inner surface of the test pipe. The details of the shop procedures are not pertinent here, but it should be acknowledged that it is a frustrating experience which involves many unsuccessful trials. The difficulty results from the requirement that the sand coating be attached uniformly and firmly to a relatively thin coat of varnish. Two degrees of roughness were produced by this method. For the first (sand-roughness I, test-series C), the sand used was of such size and shape that it passed a No. 12 Taylor sieve and was retained on a No. 14 sieve. For the second (sand-roughness II, test-series D), the sand used was such that it passed a No. 6 sieve and was retained on a No. 8 sieve. Using the average sieve opening to indicate the nominal sand-grain size, the corresponding grain sizes were 0.060 inch for series C and 0.112 inch for series D.

In order to determine the effective diameter of the sand-roughened pipes, the disassembled pipe was capped, sealed, and weighed dry, then filled with water and weighed again. The volume of water determined in this manner was used to compute the diameter of the pipe. The average diameter was 3.024 inches for the series-C pipe and 2.976 inches for the series-D pipe. From the corresponding sand-grain sizes and pipe diameters, the relative roughness was 0.020 for series C and 0.038 for series D.

It is observed that the sand used to provide pipe-wall roughness for this investigation was angular and irregular in shape, quite unlike the standard sand used in the classic tests by Nikuradse (1950). Furthermore, the sand coat was not covered with a seal coat of varnish whereas Nikuradse did use a seal coat. Consequently, for equal values of the relative-roughness ratio, the effective roughness of the sand used for this investigation was considerably greater than that used by Nikuradse.

#### PIPE ENTRANCE FOR RESISTANCE TESTS

A smooth, round entrance was used for the tests made to determine the normal resistance characteristics of the test pipes. The entrance piece was fabricated from wood, sanded smooth, and painted. The

cylindrical throat was carefully matched to the end of the test pipe to prevent disturbance due to flow separation.

#### ROUGH SLEEVE

For series-B tests a 6-inch long sleeve of deformed expanded metal was placed at the entrance to the smooth-walled test pipe. The sleeve was made from a single piece of  $\frac{1}{4}$ -inch by 18-gage unflattened expanded metal. Parts of the metal fabric were cut and bent inward approximately one-fourth inch to produce an exaggerated wall roughness at the beginning of the enlargement. Photographs of the sleeve are shown in plate 3*D,E*.

### EXPERIMENTAL METHOD AND ANALYSIS OF RESULTS

#### NORMAL-RESISTANCE TESTS

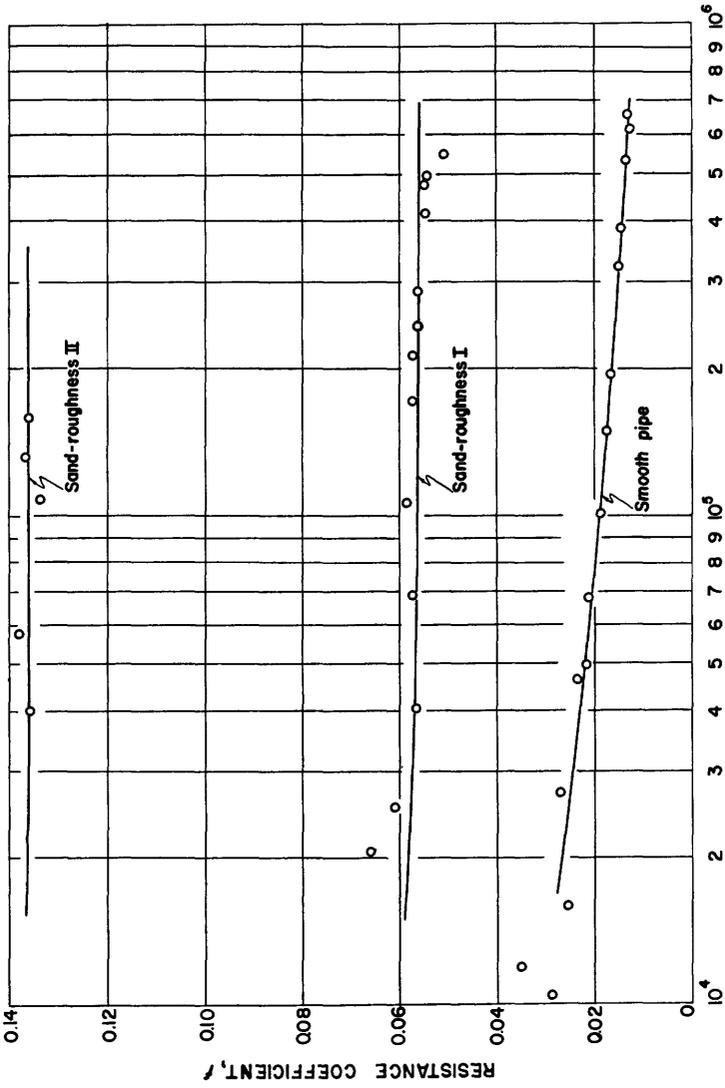
The uniform-flow resistance characteristics of the test pipes were determined as a basis for arbitrarily separating the normal resistance loss from the total measured loss for the abrupt-enlargement tests. The tests involved measurement of the discharge and the piezometric profile in the test reach. They covered a range of values of the Reynolds number which was limited by the available water supply.

Values of the hydraulic gradient used to compute the resistance coefficient,  $f$ , in the Darcy-Weisbach formula (eq 1) were determined as the slopes of lines fitted to the downstream, straight parts of the piezometric profiles. The length of the test pipes was 80 times their diameter, and the entrance to the test section was designed to prevent disturbance in the flow. For the conditions of the tests, the results of experiments by Shapiro and Smith (1948) and others indicate that normal values of the resistance coefficient were attained in the downstream part of the pipe.

Computed values of  $f$  were plotted as functions of the pipe Reynolds number [ $R_2 = (V_2 D_2) / \nu$ ]. Trends indicated by Colebrook-White transition curves were used as a guide in drawing smooth curves through the plotted points. A summary of the results of the resistance tests is shown in figure 3. The curves shown were used in the reduction and analysis of the enlargement tests.

#### ENLARGEMENT TESTS

The scope of the enlargement tests is indicated by the summary shown in table 1. A total of 115 tests was made. The enlargement ratios tested ranged from 1.5 to 16.5, and the pipe Reynolds numbers were mainly in the range between  $10^4$  and  $10^6$ .



PIPE REYNOLDS NUMBER,  $R_2$

FIGURE 3.—Summary of normal-resistance tests.

TABLE 1.—Scope of enlargement tests

Series	Test Nos.	Condition of downstream pipe	Nozzles tested (No.)	Experimenter	Summary of results (table No.)
A	1-56	Smooth	1, 2, 3, 4, 5, 6	B. M. Kittle	2
B	57-74	Smooth, with sleeve	2, 4, 6	-----do-----	3
C	75-100	Sand-roughness I	2, 3, 4, 5, 6	F. H. Ruggles	4
D	101-115	Sand-roughness II	1, 2, 4, 5, 6	-----do-----	5

The test procedure consisted of measuring the discharge and determining the piezometric profile for each setup. From the plotted and smoothed profiles, values of a total-loss coefficient were computed for each test. The coefficient,  $C_L$ , is defined by the equation

$$C_L = \frac{h_1 + \frac{V_1^2}{2g} - h_2 - \frac{V_2^2}{2g}}{\frac{V_2^2}{2g}} = \frac{H_L}{\frac{V_2^2}{2g}}, \quad (3)$$

in which  $h_1$  and  $V_1$  are the piezometric head and average velocity, respectively, in the throat of the nozzle, and  $h_2$  and  $V_2$  are the corresponding quantities at a section arbitrarily taken to be at a distance of 25 pipe diameters downstream from the beginning of the enlargement. Thus,  $H_L$  is the nominal total head loss in the first 25 pipe diameters downstream from the enlargement.

The length of the test reach used to evaluate  $H_L$  is not critical. It should be sufficient to contain most of the nonuniform flow resulting from the enlargement, but it should not be so great as to make the nominal enlargement loss,  $H_B$  (eq 2), excessively small in comparison with  $H_f$  (eq 1). The 25-diameters length was selected for several reasons. The measured hydraulic gradients at the end of the 25-diameters reach compared favorably with the corresponding gradients for uniform flow as determined from the normal-resistance tests. Furthermore, Fleetwood<sup>4</sup> showed that the velocity distribution at that section was very nearly normal in comparison with velocities computed from the Karman-Prandtl equations for uniform, turbulent flow near smooth boundaries. From his own tests, Kalinske (1947) concluded that the disturbance caused by the enlargement was virtually dissipated within a reach of 17 diameters, whereas Schütt (1926) concluded that uniform flow was restored within 8 diameters. It is concluded that the 25-diameters reach is adequate for the purpose of this investigation.

<sup>4</sup> See footnote 2, p. 54.

The principal results of the enlargement tests are shown in tables 2 through 5. In these tables,  $C_f$  is a nondimensional resistance coefficient which is derived from equation 1,

$$C_f = \frac{H_f}{\frac{V_2^2}{2g}} = f \frac{L}{D} \quad (4)$$

For the nominal 25-diameters reach,  $C_f$  is simply  $25f$ .

The coefficient  $C_B$  in tables 2 through 5 is an enlargement-loss coefficient which is obtained from equation 2. For abrupt enlargements,  $K_B$  in that equation is theoretically equal to 1.0. Thus,

$$C_B = \frac{H_B}{\frac{V_2^2}{2g}} = \left( \frac{A_2}{A_1} - 1 \right)^2 \quad (5)$$

In the conventional procedure for computing the total head loss resulting from an abrupt enlargement,  $H_f$  is added to  $H_B$ . Therefore, to obtain a computed total-loss coefficient which is comparable with  $C_L$ ,  $C_f$  was added to  $C_B$ . It follows that the ratio of  $C_L$  to  $(C_B + C_f)$  is a direct nondimensional measure of the adequacy of the conventional computation procedure.

Figures 4 through 9 show  $C_L/(C_B + C_f)$  plotted as a function of  $\mathbf{R}_2$  from the experimental data obtained in this investigation. Different symbols are used to identify the test series described in table 1. All the tests for a given nozzle are shown on a single figure. Small variations in the enlargement ratio result from differences in the pipe diameter caused by the addition of sand (as roughness) to the inner surface of the test pipe.

#### EVALUATION OF RESULTS

The results of the laboratory tests made for this investigation were expected to yield answers to the following questions:

1. Is the conventional procedure for computing the total energy loss adequate for practical purposes?
2. Is there any correlation between the accuracy of the conventional procedure and the roughness of the downstream pipe wall?
3. Can the inadequacies of the conventional procedure, if any, be correlated with observed flow characteristics?

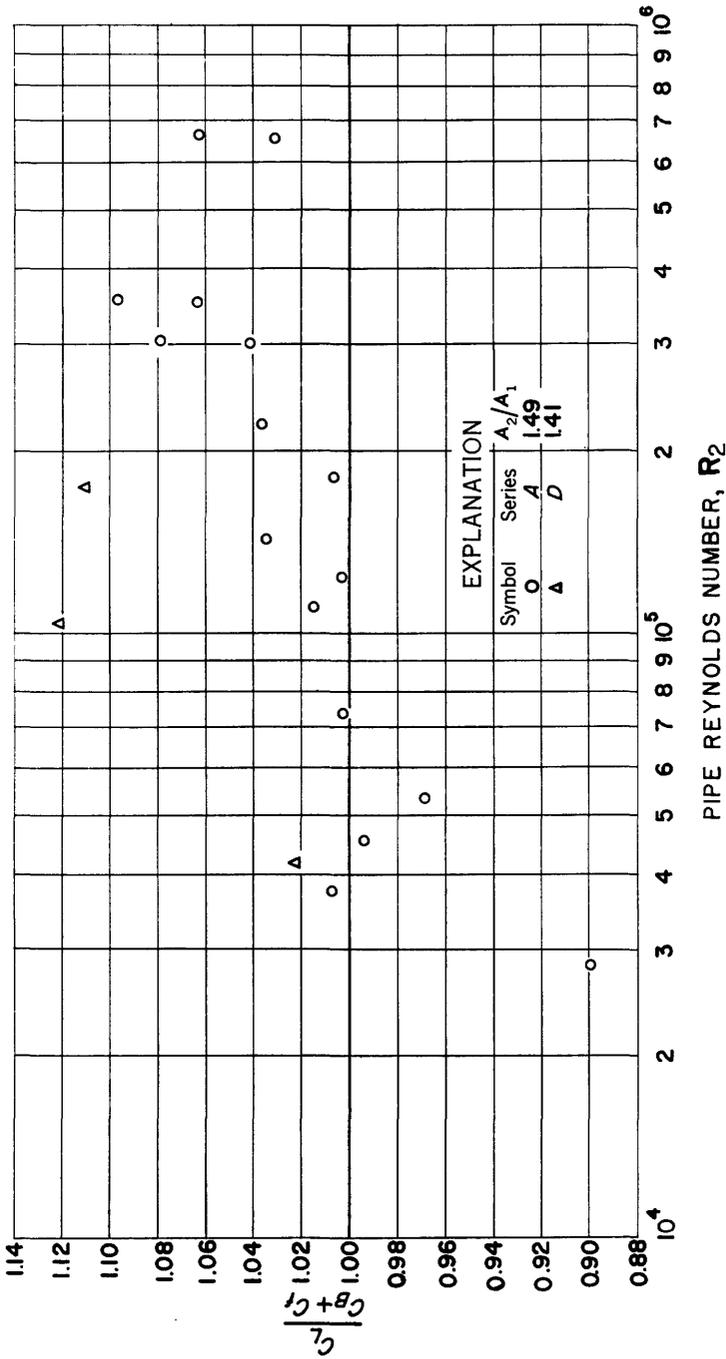
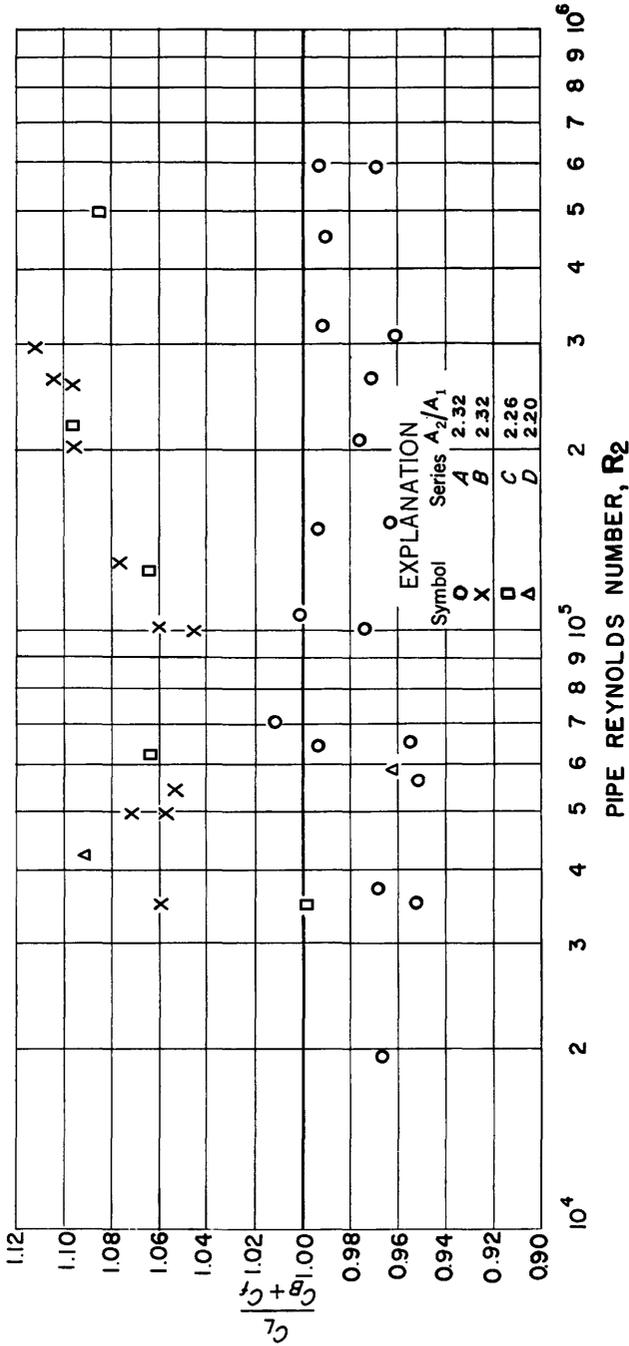


FIGURE 4.—Summary of enlargement tests, nozzle 1.



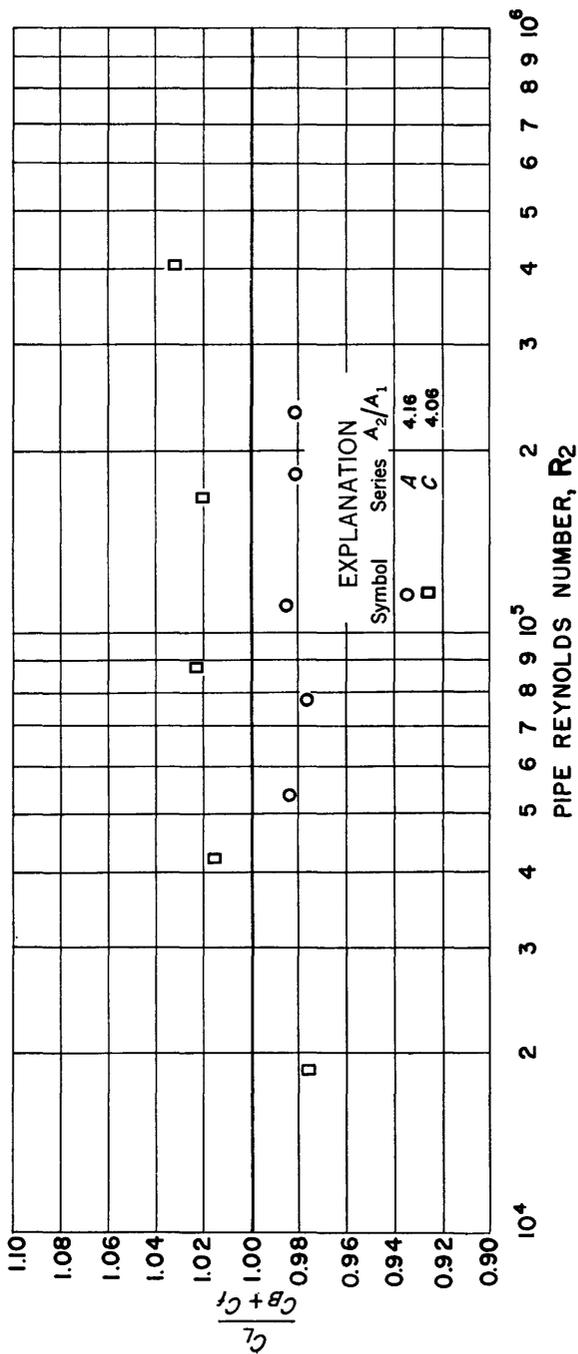


FIGURE 6.—Summary of enlargement tests, nozzle 3.

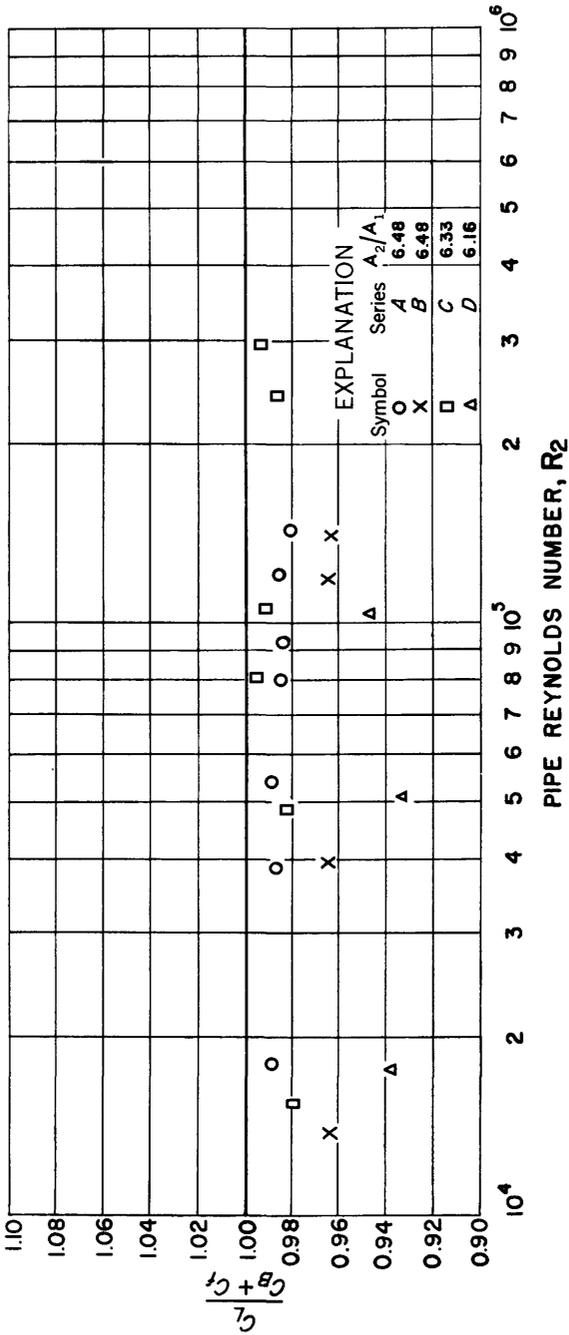


FIGURE 7.—Summary of enlargement tests, nozzle 4.

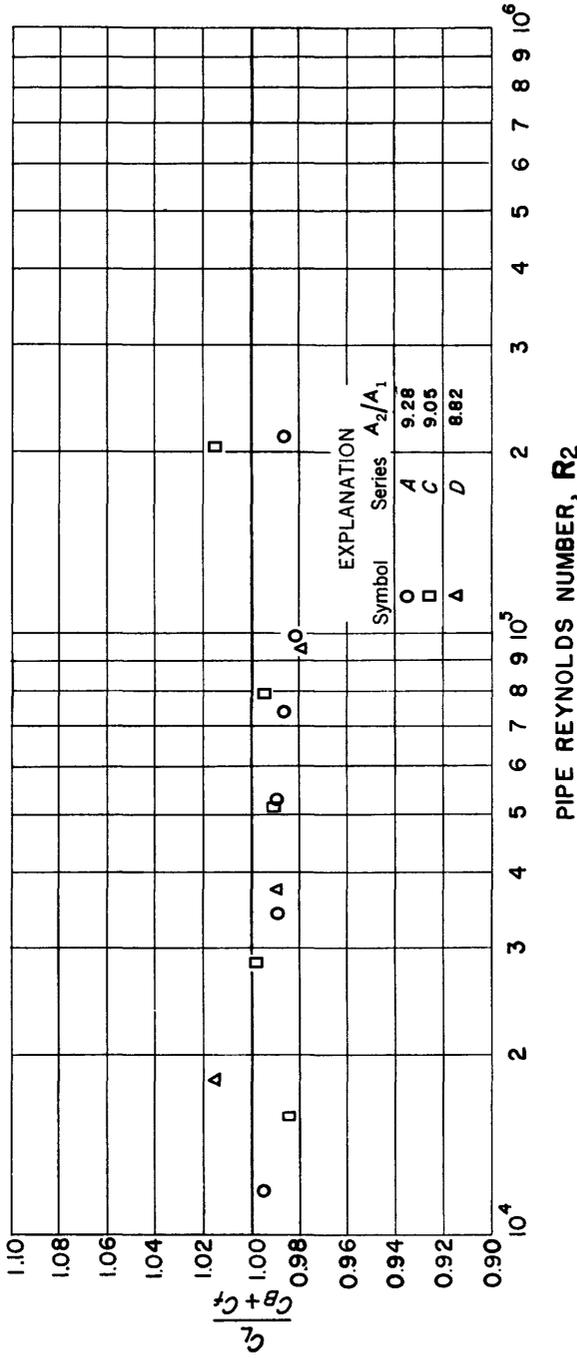
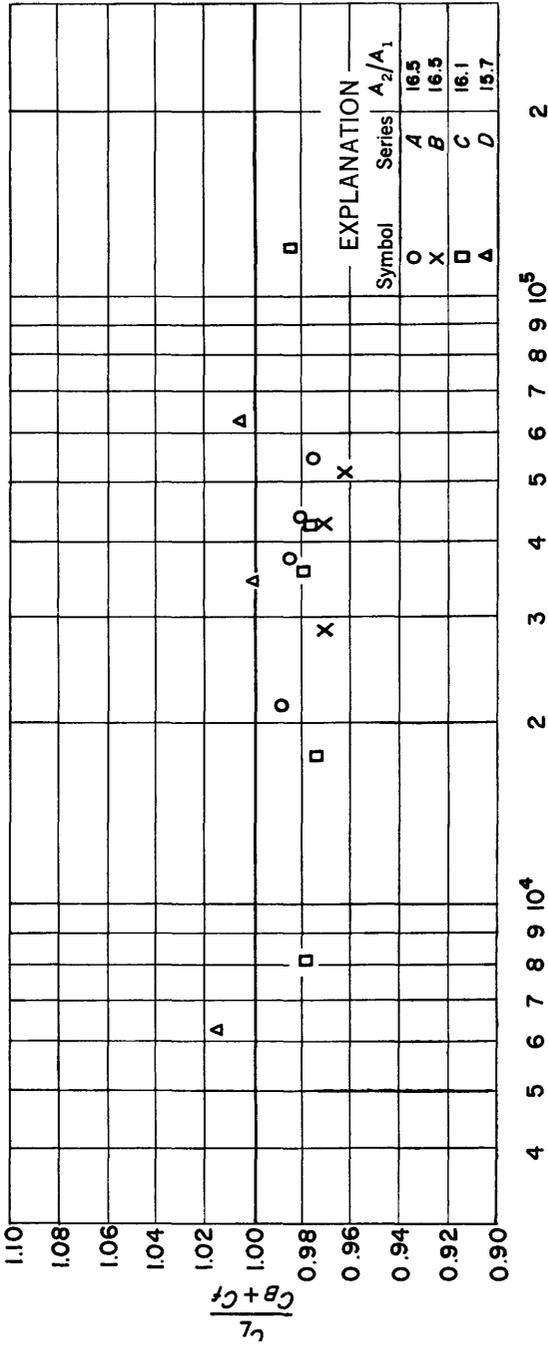


FIGURE 8.—Summary of enlargement tests, nozzle 5.



PIPE REYNOLDS NUMBER,  $R_2$

FIGURE 9.—Summary of enlargement tests, nozzle 6.

To obtain the answers to these questions, the experimental results shown on figures 4-9 were evaluated in the light of the following facts:

1. In the practical application of the conventional procedure for computing  $H_L$ , the resistance coefficient  $f$  and the areas  $A_1$  and  $A_2$  are associated with commercial pipes of various kinds and conditions. Areas are seldom known exactly, and resistance coefficients can only be estimated.
2. It is generally agreed that 5 percent is a maximum probable accuracy for computed values of  $H_f$  based on estimated values of  $f$ .
3. Computed values of  $H_B$  are critically influenced by the accuracy of measurement of  $A_2$  and  $A_1$ . Furthermore, when  $A_2/A_1$  is large, the enlargement loss is a dominant part of  $H_L$  in short pipe systems.
4. Kalinske and others have shown that upstream flow conditions have a large influence on the flow in an abrupt enlargement. In this investigation the effect of upstream disturbances, velocity distribution, and similar variables was eliminated by the use of short, smooth nozzles at the entrance to the enlargement. Thus, the independent influence of upstream flow conditions is not apparent in the results of the laboratory tests.
5. Comparison of values of  $C_L$  and  $C_f$  with values of  $C_B$  should take into consideration the fact that values of  $C_L$  and  $C_f$  are directly related to the length of the test reach used to evaluate the total head loss and the nominal resistance loss. On the other hand,  $C_B$  is independent of pipe length. Values of the ratio  $C_L/(C_B+C_f)$  are influenced slightly by the length of the test reach, but the generality of the conclusions based on that ratio is unaffected.
6. The relative accuracy of the experimental results expressed in terms of  $C_L/(C_B+C_f)$  increases as  $A_2/A_1$  increases. This conclusion is supported by the fact that the spread in plotted points in figure 9 ( $A_2/A_1=15.7$  to  $16.5$ ) is appreciably less than that in figure 4 ( $A_2/A_1=1.41$  to  $1.49$ ). The trend indicated by this comparison is substantiated by figures 5 through 8.

In preliminary reports on the results of this investigation, certain conclusions were drawn from an analysis of residual quantities such as  $(C_L-C_f)$  and  $(C_L-C_B)$ . Considering the fact that neither  $C_f$  nor  $C_B$  can be assumed to be exact, conclusions based on the residuals are believed to be misleading. One conclusion resulted in the decision to make the series-B tests. Thus, from the results of some early tests it was indicated that pipe-wall roughness might cause a reduction in the residual enlargement loss  $(C_L-C_f)$ . In explanation, it was suggested that wall roughness might retard and, therefore, reduce the energy requirements of the major eddy which occurs in the separation zone at the entrance to the enlargement. To test this hypothesis, a short, rough sleeve (pl. 3 *D*, *E*) was placed in the region occupied by the

eddy. The downstream pipe was otherwise the same as it was for test-series A. The preliminary conclusion was not substantiated by the results of the series B tests shown on figures 5, 7, and 9.

### CONCLUSIONS

From a critical analysis of the experimental results shown on figures 4 through 9, with attention to the criteria described in the preceding section and the limitations imposed by the conditions of the tests, it is concluded that the conventional method of computing the total energy loss in a pipe system containing an abrupt enlargement gives results which are in good agreement with measured losses. The experiments revealed no independent influence of pipe-wall roughness which could be associated specifically with the diffusion process. It is observed, however, that the experimental method used for this investigation is not well suited to a study of the flow mechanism.

The extent to which these conclusions are transferrable to open-channel enlargements is conjectural. Nevertheless, the results are believed to substantiate the original decision to exclude the subject of this study from the scope of the bridge-waterway investigation.

TABLE 2.—*Summary of test results, series A*

Test No.	$\frac{A_2}{A_1}$	$R_2 \times 10^{-4}$	$C_L$	$C_f$	$C_B$	$C_B + C_f$	$\frac{C_L}{C_B + C_f}$
1.....	1. 49	30. 5	0. 660	0. 375	0. 237	0. 612	1. 079
2.....	1. 49	22. 1	. 661	. 400	. 237	. 637	1. 037
3.....	1. 49	14. 3	. 700	. 440	. 237	. 677	1. 034
4.....	1. 49	11. 0	. 710	. 463	. 237	. 700	1. 014
5.....	1. 49	7. 33	. 742	. 503	. 237	. 740	1. 003
6.....	1. 49	5. 35	. 750	. 538	. 237	. 775	. 968
7.....	1. 49	3. 76	. 821	. 578	. 237	. 815	1. 007
8.....	1. 49	35. 5	. 661	. 365	. 237	. 602	1. 097
9.....	1. 49	66. 2	. 607	. 335	. 237	. 572	1. 062
10.....	1. 49	30. 1	. 640	. 378	. 237	. 615	1. 041
11.....	1. 49	18. 1	. 659	. 418	. 237	. 655	1. 006
12.....	1. 49	12. 4	. 692	. 453	. 237	. 690	1. 003
13.....	1. 49	4. 56	. 787	. 555	. 237	. 792	. 994
14.....	1. 49	2. 82	. 765	. 613	. 237	. 850	. 900
15.....	1. 49	35. 2	. 640	. 365	. 237	. 602	1. 063
16.....	1. 49	65. 2	. 590	. 335	. 237	. 572	1. 032
17.....	2. 32	59. 0	2. 01	. 338	1. 74	2. 07	. 970
18.....	2. 32	45. 4	2. 07	. 353	1. 74	2. 09	. 991
19.....	2. 32	21. 0	2. 09	. 405	1. 74	2. 14	. 977
20.....	2. 32	10. 7	2. 21	. 473	1. 74	2. 21	1. 001
21.....	2. 32	6. 45	2. 24	. 518	1. 74	2. 25	. 994
22.....	2. 32	14. 8	2. 16	. 438	1. 74	2. 17	. 994
23.....	2. 32	32. 1	2. 09	. 373	1. 74	2. 11	. 991
24.....	2. 32	5. 60	2. 16	. 533	1. 74	2. 27	. 952
25.....	2. 32	3. 71	2. 24	. 580	1. 74	2. 32	. 968

TABLE 2.—*Summary of test results, series A—Continued*

Test No.	$\frac{A_2}{A_1}$	$R_2 \times 10^{-4}$	$C_L$	$C_f$	$C_B$	$C_B + C_f$	$\frac{C_L}{C_B + C_f}$
26	2.32	1.95	2.32	0.663	1.74	2.40	0.967
27	2.32	26.6	2.06	.385	1.74	2.12	.972
28	2.32	6.56	2.15	.515	1.74	2.25	.955
29	2.32	10.1	2.15	.473	1.74	2.21	.974
30	2.32	7.03	2.27	.508	1.74	2.24	1.012
31	2.32	15.2	2.09	.435	1.74	2.17	.963
32	2.32	3.53	2.21	.585	1.74	2.32	.952
33	2.32	31.3	2.03	.375	1.74	2.11	.962
34	2.32	59.8	2.06	.338	1.74	2.07	.994
35	4.16	18.4	10.2	.418	9.99	10.4	.982
36	4.16	11.2	10.3	.438	9.99	10.4	.985
37	4.16	7.76	10.2	.498	9.99	10.5	.977
38	4.16	5.40	10.4	.538	9.99	10.5	.983
39	4.16	23.1	10.2	.405	9.99	10.4	.982
40	6.48	12.2	30.1	.455	30.1	30.5	.986
41	6.48	5.46	30.2	.535	30.1	30.6	.989
42	6.48	9.29	30.1	.490	30.1	30.6	.985
43	6.48	8.00	30.1	.495	30.1	30.6	.985
44	6.48	3.88	30.2	.575	30.1	30.6	.987
45	6.48	1.80	30.4	.672	30.1	30.7	.989
46	6.48	14.3	29.9	.440	30.1	30.5	.981
47	9.28	1.18	68.9	.735	68.5	69.2	.995
48	9.28	3.41	68.3	.583	68.5	69.1	.989
49	9.28	5.28	68.3	.540	68.5	69.0	.989
50	9.28	7.31	68.0	.505	68.5	69.0	.986
51	9.28	9.90	67.8	.475	68.5	69.0	.982
52	9.28	21.2	68.1	.405	68.5	69.0	.987
53	16.5	2.15	239	.635	241	242	.989
54	16.5	3.77	238	.578	241	242	.985
55	16.5	4.34	237	.560	241	242	.981
56	16.5	5.44	236	.535	241	242	.976

TABLE 3.—Summary of test results, series B

Test No.	$\frac{A_2}{A_1}$	$R_2 \times 10^{-4}$	$C_L$	$C_f$	$C_B$	$C_B + C_f$	$\frac{C_L}{C_B + C_f}$
57	2.32	25.6	2.33	0.389	1.74	2.12	1.096
58	2.32	20.2	2.34	.400	1.74	2.14	1.096
59	2.32	12.9	2.35	.449	1.74	2.18	1.076
60	2.32	10.0	2.31	.473	1.74	2.21	1.046
61	2.32	5.45	2.39	.536	1.74	2.27	1.053
62	2.32	5.00	2.41	.545	1.74	2.28	1.057
63	2.32	3.51	2.46	.587	1.74	2.32	1.059
64	2.32	29.6	2.35	.378	1.74	2.11	1.112
65	2.32	26.1	2.34	.388	1.74	2.12	1.103
66	2.32	10.1	2.34	.472	1.74	2.21	1.060
67	2.32	4.98	2.44	.545	1.74	2.28	1.071
68	6.48	11.9	29.5	.456	30.1	30.5	.967
69	6.48	3.98	29.5	.473	30.1	30.5	.965
70	6.48	1.39	29.6	.710	30.1	30.8	.963
71	6.48	14.2	29.4	.440	30.1	30.5	.963
72	16.5	4.26	235	.550	241	242	.971
73	16.5	2.85	235	.613	241	242	.972
74	16.5	5.18	233	.540	241	242	.963

TABLE 4.—Summary of test results, series C

Test No.	$\frac{A_2}{A_1}$	$R_2 \times 10^{-4}$	$C_L$	$C_f$	$C_B$	$C_B + C_f$	$\frac{C_L}{C_B + C_f}$
75	2.26	49.6	3.24	1.40	1.59	2.99	1.085
76	2.26	3.50	3.00	1.42	1.59	3.01	.998
77	2.26	6.21	3.20	1.42	1.59	3.01	1.064
78	2.26	12.6	3.18	1.40	1.59	2.99	1.064
79	2.26	21.9	3.28	1.40	1.59	2.99	1.096
80	4.06	40.7	11.1	1.40	9.37	10.8	1.032
81	4.06	1.88	10.6	1.45	9.37	10.8	.976
82	4.06	4.23	11.0	1.42	9.37	10.8	1.015
83	4.06	8.82	11.0	1.40	9.37	10.8	1.024
84	4.06	16.9	11.0	1.40	9.37	10.8	1.020
85	6.33	1.56	29.2	1.45	28.4	29.8	.980
86	6.33	4.82	29.3	1.42	28.4	29.8	.983
87	6.33	10.6	29.5	1.40	28.4	29.8	.992
88	6.33	24.2	29.4	1.40	28.4	29.8	.987
89	6.33	29.6	29.6	1.40	28.4	29.8	.994
90	6.33	8.04	29.6	1.40	28.4	29.8	.996
91	9.05	20.4	67.2	1.40	64.8	66.2	1.015
92	9.05	1.59	65.3	1.45	64.8	66.3	.985
93	9.05	2.88	66.1	1.42	64.8	66.2	.998
94	9.05	5.16	65.6	1.42	64.8	66.2	.991
95	9.05	7.94	65.9	1.40	64.8	66.2	.995
96	16.1	12.0	227	1.40	229	230	.985
97	16.1	.810	225	1.50	229	231	.978
98	16.1	1.77	224	1.45	229	231	.973
99	16.1	3.57	226	1.42	229	230	.980
100	16.1	4.27	225	1.42	229	230	.977

TABLE 5.—Summary of test results, series D

Test No.	$\frac{A_2}{A_1}$	$R_2 \times 10^{-4}$	$C_L$	$C_f$	$C_B$	$C_B + C_f$	$\frac{C_L}{C_B + C_f}$
101.....	1. 41	17. 4	3. 96	3. 40	0. 171	3. 57	1. 110
102.....	1. 41	4. 16	3. 65	3. 40	. 171	3. 57	1. 022
103.....	1. 41	10. 4	4. 00	3. 40	. 171	3. 57	1. 120
104.....	2. 20	14. 1	5. 95	3. 40	1. 45	4. 85	1. 227
105.....	2. 20	4. 24	5. 29	3. 40	1. 45	4. 85	1. 091
106.....	2. 20	5. 93	4. 68	3. 40	1. 45	4. 85	. 965
107.....	6. 16	10. 4	28. 5	3. 40	26. 7	30. 1	. 948
108.....	6. 16	1. 77	28. 2	3. 40	26. 7	30. 1	. 938
109.....	6. 16	5. 10	28. 1	3. 40	26. 7	30. 1	. 933
110.....	8. 82	9. 40	61. 7	3. 40	59. 6	63. 0	. 979
111.....	8. 82	1. 78	63. 9	3. 40	59. 6	63. 0	1. 014
112.....	8. 82	3. 74	62. 2	3. 40	59. 6	63. 0	. 988
113.....	15. 7	6. 26	222	3. 40	217	220	1. 006
114.....	15. 7	. 625	224	3. 42	217	220	1. 015
115.....	15. 7	3. 42	220	3. 40	217	220	1. 001

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